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E0 TRANSITIONS BETWEEN LOWEST $K^\pi = 0^+$ BANDS IN ^{232}U AND ^{234}U

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Regular patterns of E0 transitions were observed after $^{232}\text{Th}(\alpha, xn)$ reactions. They indicate that the moments of inertia of β - and ground-state bands are nearly equal in ^{234}U , in contrast to its even-even neighbours ^{232}Th , ^{232}U and ^{236}U .

Experimental studies of short-lived actinide nuclei often suffer from a strong fission-induced background. As pointed out in refs. [1] and [2], conversion electron spectroscopy has distinct advantages with respect to γ -ray spectroscopy due to the favourable Z -dependence of the conversion process. This letter asks attention for the observational advantages of the strong E0 admixtures to transitions between states with equal J^π and K quantum numbers. Application to interband transitions between β - and ground-state (gs) bands in $^{232,234}\text{U}$ resulted in the identification of higher-spin β -band members. This enabled us to recognize new properties of the β - and gs-band moments of inertia in $^{232,234}\text{U}$ and neighbouring even-even nuclei.

Transitions between states with equal spin, parity and K -quantum numbers proceed predominantly via E2, M1 and E0 radiation. In heavier nuclei the E0 probability competes more and more favourably. For instance, between 0.5 and 1 MeV and for $Z \approx 80$ the E0 transition probability (totally converted) roughly increases [3,4] as Z^{12} , in contrast with the single-particle estimate for E2 ($\approx Z^{1.6}$) and for M1 (independent of Z) γ -radiation. The E2 and M1 conversion probabilities are roughly proportional to Z^5 and Z^7 , respectively. Total conversion coefficients $\alpha_{\text{tot}}(\text{E2})$ for pure E2 transitions of 1 MeV are of order 10^{-2} , while the α_{tot} of the present E0-admixed transitions

are larger by about two orders of magnitude. Although a sizeable M1 contribution cannot be excluded experimentally, it will not affect the following conclusions and will be ignored.

The larger E0 admixture to interband transitions in $^{232,234}\text{U}$ provided us with a sensitive means to study higher-spin members of the β -bands. Rotational bands can be characterized by their moments of inertia $J(\omega)$ where ω is the rotational frequency. As a general rule β -bands have larger moments of inertia than ground-state bands. For $\Delta J = 0$, $\beta \rightarrow \text{gs}$ interband transitions this becomes evident as a decrease in transition energy with increasing spins $J_i = J_f$. An example of this behaviour is presented in fig. 1a for ^{232}U , where the energy spacings between interband transitions are 10 to 20 keV. Wider spacings are more common, e.g. in ^{232}Th , ^{236}U and in several known cases for deformed rare-earth nuclei. However, in the case of ^{234}U we found the striking situation that the level separations within the two bands are nearly identical, so that the spectrum of the $\Delta J = 0$ interband transitions shows a nearly degenerate pattern with energy spacings of less than 5 keV (fig. 1b). Consequently, the two bands under consideration have nearly equal moments of inertia up to spin 8^+ .

The new experimental results are based on observations of in-beam conversion electrons after the $^{232}\text{Th}(\alpha, 2n)^{234}\text{U}$ and $^{232}\text{Th}(\alpha, 4n)^{232}\text{U}$ reactions at respective beam energies of 25 and 40 MeV. The use of two mini-orange spectrometers [5], facing the target at 135° on both sides of the α -beam, facilitated simultaneous measurements with different energy win-

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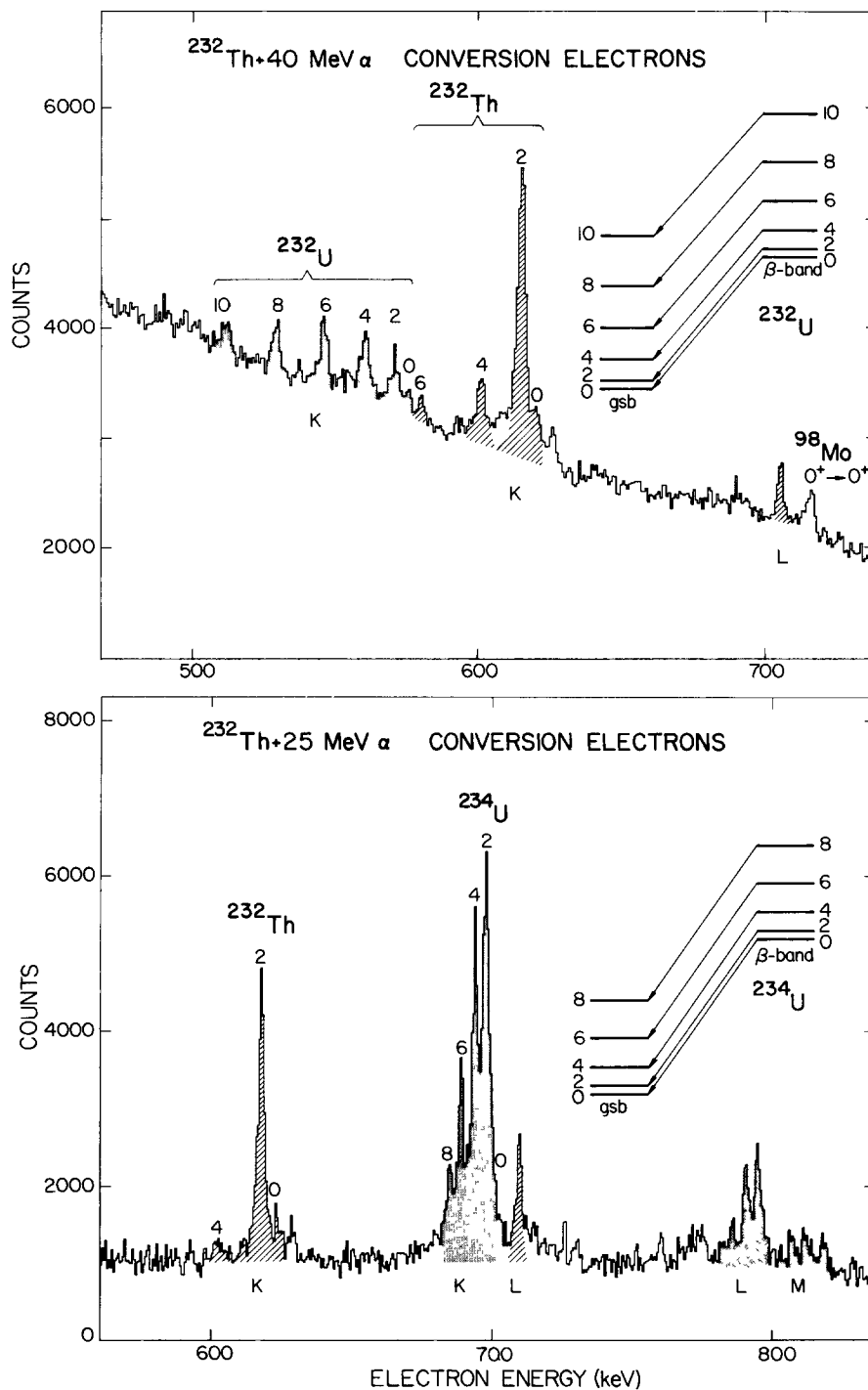


Fig. 1. Spectra of prompt conversion electrons after $^{232}\text{Th}(\alpha, xn)$ reactions, showing clusters of E0-admixed transitions in the target nucleus ^{232}Th (hatched) and in ^{232}U (a), ^{234}U (b) (shaded). Insets illustrate the relevant level structure.

dows. Singles electron spectra were time-differentiated in 10 ns intervals with respect to the cyclotron beam bursts. The E0-admixed actinide transitions were found in prompt electron spectra (fig. 1), while two other E0 transitions became visible after β -decay of fission fragments: at 787 keV (^{98}Mo) and at 854 keV (^{98}Zr). The ^{232}Th target thickness was 1 mg/cm², sufficiently thin to allow escape of fission fragments but sufficiently thick to stop the recoiling actinide nuclei. During the ^{232}U studies e-e and e- γ coincidences were recorded as well.

A search for corresponding γ -rays required a more specialized approach. For the (α , 2n) case, with less interference from fission than the (α , 4n) reaction, an attempt was made with a Ge(Li)-NaI anti-Compton spectrometer placed at 1 m from the target. This arrangement facilitated both shielding of the NaI crystal as well as time-of-flight discrimination of the neutron-induced background. In prompt γ -ray spectra a few transitions in ^{234}U could thus be identified, but none of the $\Delta J = 0$ transitions between β - and gs-band. The resulting limits on K -conversion coefficients are listed in table 1. The Nuclear Data Sheets evaluation [6] for the $2_\beta \rightarrow 2_{gs}$ and $4_\beta \rightarrow 4_{gs}$ transitions arrived at finite and seemingly different α_K values of 2.6 and 0.45, respectively. We estimate, however, that these values have to be assigned with uncertainties as large as (40–60)%. In fact, it may be expected on theoretical grounds [7] that the E0 admixtures (and α_K values) will be spin-independent to within 10%.

Multipolarities of the strong conversion electron lines cannot be larger than $L = 2$ since they are prompt

to within 10 ns. This, and the fact that the α_K values exceed those for E2 radiation by about two orders of magnitude, confirms the E0 character of the $\Delta J = 0$, $\beta \rightarrow gs$ transitions.

From radioactive decay the states of the β -bands in ^{232}U were known up to $J^\pi = 4^+$. Our results extend the knowledge of these bands up to higher spins: $J^\pi = 6^+$ at 985.2 ± 0.3 keV, 8^+ at 1187.3 ± 0.4 keV and 10^+ at 1434.9 ± 0.6 keV in ^{232}U ; $J^\pi = 6^+$ at 1095.7 ± 0.2 keV and 8^+ at 1292.7 ± 0.2 keV in ^{234}U .

Besides the E0 admixed transitions the conversion electron spectra show a number of weaker lines. Most of these could be identified with transitions connecting the γ - and gs-bands in the Th and U nuclei. They are visible despite the fact that a significant E0 admixture can be excluded because of K -forbiddenness. However, the intensity patterns of the conversion electron lines in fig. 1 are somewhat deceptive: the strong E0 lines belong to weak transitions. In fact, for the ^{234}U measurements the population of γ -band states is stronger by at least a factor of 5 than the population of β -band states. In the case of ^{232}U the feeding of the β -band is found to be of the order of 1% of that of the gs band. It may be noted that the $O_\beta \rightarrow O_{gs}$ transitions are clearly present in both spectra in fig. 1, though unresolved in the ^{234}U investigation.

The $\Delta J = 0$, $\beta \rightarrow gs$ transitions show regular patterns. Particularly striking is the case of ^{234}U where the transition energies become nearly identical. In terms of a rotational band description the small energy differences are due to a near equality of the moments of inertia for the corresponding bands. Goerlach et al.

Table 1.

Observed $\Delta J = 0$ transitions between the beta-bands and ground-state bands in ^{232}U and ^{234}U . For each transition the measured energy (E_{tr}) and the relative intensity (I_K) of the K conversion line is given.

$J_i \rightarrow J_f$	^{234}U			^{232}U	
	E_{tr} (keV)	I_K	α_K	E_{tr} (keV)	I_K
$10_\beta \rightarrow 10_{gs}$				628.4 ± 0.4	35 ± 10
$8_\beta \rightarrow 8_{gs}$	795.7 ± 0.2	22 ± 2	> 0.2	645.5 ± 0.3	54 ± 10
$6_\beta \rightarrow 6_{gs}$	799.7 ± 0.2	47 ± 2	> 0.3	662.2 ± 0.2	92 ± 10
$4_\beta \rightarrow 4_{gs}$	804.5 ± 0.2	76 ± 2	> 0.7	676.5 ± 0.2	114 ± 10
$2_\beta \rightarrow 2_{gs}$	$808.25^a)$	$100^b) \pm 4$	> 0.5	686.6 ± 0.2	$100^b) \pm 15$
$0_\beta \rightarrow 0_{gs}$	810.1 ± 0.5	36 ± 4		691.3 ± 0.5	50 ± 10

a) Calibration value from ref. [6].

b) Normalization value.

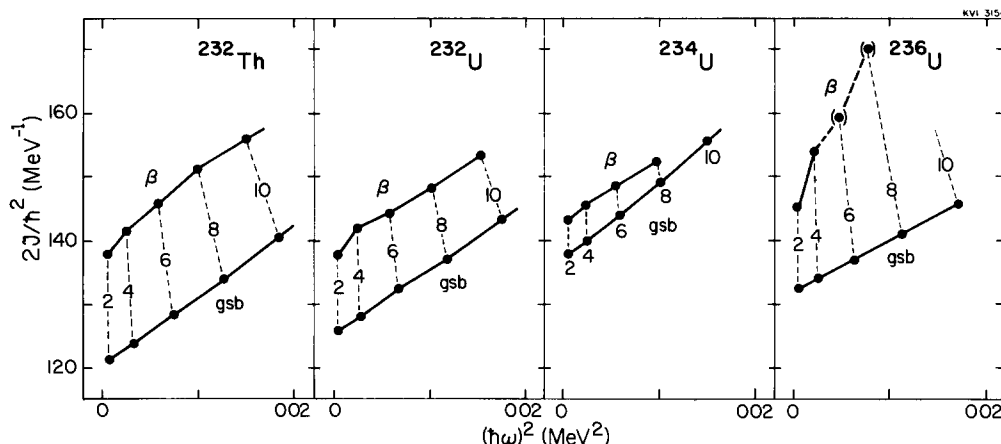


Fig. 2. Moments of inertia versus rotational frequency for the beta and ground-state bands in ^{232}U , ^{234}U and the neighbouring even-even nuclei ^{232}Th , ^{236}U .

[8] made an interesting observation of similar but unresolved E0 transitions between states in the second minima of ^{236}U and ^{238}U . Their findings indicate a similar near-equality of moments of inertia as we present for the first minimum of ^{234}U .

Fig. 2 illustrates the dependence of the β - and gs-band moments of inertia on the rotational frequency ω up to $J^\pi = 10^+$ in ^{232}Th [9], $^{232,234}\text{U}$ (present work) and ^{236}U [10]. The β - and gs-bands of the first three nuclei show approximately the same variation of $J(\omega)$ with rotational frequency. This indicates that the collective properties of these bands can be described in the same frame of reference, and that residual interactions with other orbitals do not disturb the coupling of pure rotation to a β -vibration. The behaviour of the β -band in ^{236}U deserves further investigation, since there could be interference with a second, close-lying $K^\pi = 0^+$ band.

Considering the first three nuclides presented in fig. 2, we observe that the nucleus-to-nucleus variation in the gs-band moments of inertia is much larger than for the β -bands. In summary, the new β -band states for $^{232,234}\text{U}$, in combination with similar states already known for ^{232}Th and ^{236}U , indicate that the near-equality of the β - and gs- band moments of inertia in ^{234}U is mainly due to properties of the gs band.

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